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Trend analysis of air temperature time series in Greece and their relationship with circulation using surface and satellite data: 1955–2001

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With 10 Figures

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Summary

In this study, trends of annual and seasonal surface air temperature time series were examined for 20 stations in Greece for the period 1955–2001, and satellite data for the period 1980–2001. Two statistical tests based on the least square method and one based on the Mann-Kendall test, which is also capable of detecting the starting year of possible climatic discontinuities or changes, were used for the analysis. Greece, in general, shows a cooling trend in winter for the period 1955–2001, whereas, summer shows an overall warming trend, however, neither is statistically significant. As a result, the overall trend of the annual values is nearly zero. Comparison with corresponding trends in the Northern Hemisphere (NH) shows that temperatures in Greece do not follow the intense warming trends. Satellite data indicate a remarkable warming trend in mean annual, winter and summer in Greece for the period 1980–2001, and a slight warming trend in annual, spring and autumn for the NH. Comparison with the respective trends detected in the surface air temperature for the same period (1980–2001) shows they match each other quite well in both Greece and the NH. The relationship between temperature variability in Greece and atmospheric circulation was also examined using correlation analysis with three circulation indices: the well-known North Atlantic Oscillation Index (NAOI), a Mediterranean Oscillation Index (MOI) and a new Mediterranean Circulation Index (MCI). The MOI and MCI indices show the most interesting correlation with winter temperatures in Greece. The behaviour of pressure and the height of the 500 hPa surface over the Mediterranean region supports these results.

1. Introduction

Analysis of air temperature data at global scales with respect to climate change indicates a 0.4 °C to 0.8 °C rise since 1860 (IPCC, 2001). Warming since the mid-1970s has been particularly rapid with all eight of the warmest years on record occurring since 1983 (WMO, 1997; CRU, 1997). The 1990s are quite likely to have been the warmest decade of the millennium in the Northern Hemisphere (NH) while 1998 is likely to have been the warmest year (IPCC, 2001). In particular, summer temperatures in the NH during recent decades have been the warmest in at least six centuries. The average temperature near the surface of the Earth in 1999 was the 5^{th} highest so far recorded, an estimated 0.33 °C higher than the 1961–90 average (IPCC, 2001). In spite of ongoing research on climate change conducted by various international agencies and universities, the question of whether rising global mean air temperatures is caused either by increasing emissions of greenhouse gases to the atmosphere or by natural variability of climate has not been answered satisfactorily.

In terms of analysis of satellite temperature data a very slight warming trend since 1979, has been observed in the lower troposphere, but not to the extent shown by surface observations. Major anomalies due to volcanic eruptions like Pinatubo, and ocean current phenomena like El Nino, are detected but overall the trend is near zero, about 0.04 degrees Celsius warming per decade for the 23-year period, 1979–2001 (Spencer, 2002).

Although regional differences are relatively high, most of Europe has experienced rising temperatures of about 0.8 °C during the 20th century (IPCC, 1996; IPCC, 2001). Analysis of surface air temperature observed at stations located in all regions of the Mediterranean basin, indicates similar patterns to the global or and hemispheric scale; namely a cooling during the period 1955–1975 and a strong warming during the 1980s and the first half of the 1990s (Piervitali et al., 1997). However, the east–west Mediterranean difference in air and sea surface temperature trends is distinctive. Most of the studies concerning air temperature in the Mediterranean discern a positive trend in the western Mediterranean for the period 1950–1990, and a negative trend in the eastern Mediterranean for the same period (Parker et al., 1994; Sahsamanoglou and Makrogiannis, 1992; Nicholls et al., 1996), which reinforces the concept of a Mediterranean Oscillation between the western and eastern parts of the basin (Kutiel and Maheras, 1998). The large-scale circulation, however, has been found to play an important role in temperature variability in the Mediterranean. Cullen and de Menocal (2000) detected a connection between the North Atlantic sector and the southeastern Mediterranean, which is the easternmost limit of the North Atlantic Oscillation influence on Mediterranean climate.

Regional climate variations, however, have regional features that often do not match those of the globe as a whole. Greece's orography and location in the eastern Mediterranean basin imply strong influence from the local circulation. For this reason the analysis of temperature changes in this region may be suitable to identify such differences. Indeed, Greece is differentiated from the rest of Europe in that air temperature shows a slight negative trend over the 20th century (IPCC, 1996; Mitchell and Hulme, 2000; Giles and Flocas, 1984; Retalis et al., 1998). An overall cooling trend was detected in the study of Proedrou et al. (1997) for the majority of Greek stations in winter over the entire period, 1951–1993. The same cooling trend was also recognized for the mean annual and summer values, although a reverse warming trend was detected around the mid-1970s at several stations. According to a more recent study by Luterbacher et al. (2000), winter temperatures in Greece present a cooling trend during the period 1957–1997. The 1970s has been the coldest decade of the 20th century in Greece (Giles and Flocas, 1984; Makrogiannis et al., 1998).

Many papers have been published dealing with global scale climate, this paper, however, deals with a regional scale investigation, referring specifically to Greece. The few published studies on trend analysis of air temperature in the area of Greece are based either on a single test or on extended time series of temperature for a limited number of stations. The primary aim of this study is to examine the trends of the mean annual and seasonal air temperature time series for all the available stations in Greece (20), for the longest common time period with homogenous temperature data (1955–2001), using three statistical tests. Taking into account the size of Greece and the even spatial distribution of the 20 stations, this sample may be considered as sufficient to also account for the local differences. The study also describes trend analysis of lower tropospheric temperature data from satellite measurements for the period 1980–2001 for Greece. A comparison with the corresponding trends in the NH is performed in order to examine whether trends observed in surface based and satellite temperature measurements in Greece match the overall warming trend detected at the hemispheric scale.

The secondary objective of this study is to detect regional and large-scale mechanisms which are responsible for the temperature trends around Greece. Local changes in meteorological variables in mid-latitudes are mainly controlled by the atmospheric circulation (Parker et al., 1994; Hurrel, 1995; Hurrel and Van Loon, 1997). As a consequence, a significant fraction of local variability can be explained by large-scale oscillation patterns. Concerning the Mediterranean region, only a few studies exist of the relationship between atmospheric circulation indices and temperature (Cullen and de Menocal, 2000; Kutiel and Maheras, 1998). Correlation analysis is used to relate air temperature variability in Greece with air-pressure patterns over the Mediterranean. Atmospheric circulation is represented by three indices in this study: the well known North Atlantic Oscillation Index (NAOI), a Mediterranean Oscillation Index (MOI) based on the 500 hPa geopotential height records for Cairo and Algiers, and a new Mediterranean Circulation Index (MCI) constructed from surface pressure records in Marseille and Jerusalem. In addition, the patterns of pressure and height of the 500 hPa surface over the Mediterranean region are also investigated and related to temperature trends over Greece.

2. Data and methodology

2.1 Temperature data

Monthly mean values of surface air temperature for 20 stations in Greece are used for the period 1955–2001. Figure 1 presents the location of the stations and Table 1 shows their coordinates and altitudes. Observations were examined to verify their homogeneity; this was first accomplished by selecting stations where the monitoring site has not been changed during the period of the record. The Alexandersson test (Alexandersson, 1986) was applied to examine the homogeneity of the data from the remaining stations. The Alexandersson test has the advantage over other homogeneity tests in providing information on the year of the possible shift in a station time series without using complex mathematics. The relatively homogeneity is tested by using nearby reference stations, with time series considered a-priori as homogeneous. In this study, data from four stations (Alexandroupoli, Irakleio, Mytilene, Methoni) were selected as reference series since they are considered to be homogeneous (no changes in instrumentation, observation practice and station site). The remaining 17 stations were tested using the reference series to which it showed the highest correlation. In addition, the same test was also applied without using reference time series. In this case, a statistic $T(a)$ was used to compare the mean of the first a years of the record with that of the last $n-a$ years, where n is the size of the record.

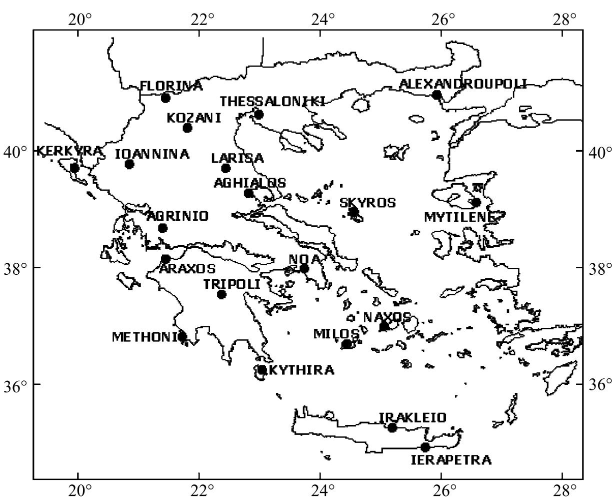

Fig. 1. Map of Greece with the locations of the 20 stations used in the study

Table 1. Geographical coordinates and altitude of the 20 stations

	Station	Latitude	Longitude	Altitude (m)
1.	Aghialos	39°13′N	22°48′E	15
2.	Agrinio	38°37′N	21°25′E	46
3.	Alexandroupoli	40°51′N	25°57′E	4
4.	Araxos	38°10′N	21°25′E	14
5.	Florina	40°48′N	21°25′E	662
6.	Ierapetra	35°00′N	25°44′E	13
7.	Ioannina	39°40′N	20°51′E	484
8.	Iraklio	35°20′N	25°11′E	48
9.	Kerkyra	39°37′N	19°55′E	2
10.	Kozani	40°20′N	21°48′E	625
11.	Kythira	36°08′N	23°00′E	167
12.	Larisa	39°38′N	22°25′E	73
13.	Methoni	36°50′N	21°43′E	34
14.	Milos	36°43′N	24°25′E	182
15.	Mytilene	39°04′N	26°35′E	5
16.	Nat. Obs. Athens	37°58′N	23°43′E	107
17.	Naxos	37°06′N	25°24′E	9
18.	Skyros	38°54′N	24°33′E	4
19.	Thessaloniki	40°37′N	22°57′E	31
20.	Tripoli	37°33′N	22°21′E	663

In the case series with a few missing observations at a station, the recorded values in neighbouring stations with high correlation (r greater than 0.8 at the 95% level of significance) were used to complete the temperature record. Missing values were found in 9 stations ranging from 1 to 12 monthly values in the entire data set.

Finally, seasonal and annual mean temperatures and their anomalies (departure from the average of the 1961–1990 period) were calculated for each of the 20 stations. Annual temperature was conventionally made to correspond to the period from December 1st to November 30th and dated by the year in which January occurred. Winter temperature refers to the interval December–January–February (and dated as for the annual value), spring as March–April–May, summer as June–July–August and autumn as September–October–November.

The corresponding time series of temperature departures from the average of the 1961–1990 period in the NH were also used. This dataset is a combination of land air temperature anomalies (Jones, 1994a) and sea surface temperature anomalies (Parker et al., 1995) on a $5^\circ \times 5^\circ$ grid-box basis, developed by the Climatic Research Unit (CRU). The dataset has been extensively used in IPCC reports.

Satellite temperature data for the area of Greece (20–28° E and 34–42° N) for the period 1979–2001, from the Microwave Sounding Unit (MSU) on board the TIROS-N series of NOAA polar orbiting satellites, were also used. In addition, the respective satellite data for the NH derived by the MSU measurements (temperature departures from the average of the 1979–2001 period) were used for comparison. The data were adjusted for time-dependent biases by NASA and the Global Hydrology and Climate Center (GHCC) at the University of Alabama in Huntsville and comprise monthly mean temperature anomalies (departures from the average of the 1979–2001 period) for the lower troposphere ranging from the surface to 8 km up. These data include all corrections: non-linear diurnal adjustment, orbit decay, instrument-body effects etc. Concerning the accuracy of the MSU measurements, an excellent agreement between the two independent, direct atmospheric temperature measurements from radiosondes and satellites, has been found in recent studies (Hurrel et al., 2000; Christy et al., 2000).

MSU is a microwave atmospheric sounder providing information on the distribution of microwave radiation emitted by the atmosphere from which vertical profiles of temperature through clouds up to 20 km in altitude, may be obtained. In general, sounders operate in nadir viewing mode and perform passive measurements of the radiation only in a finite number of channels aligned with the spectral features associated with the species under observation. In particular, MSU is a four-channel radiometer making passive measurements in four regions of the 5.5 mm oxygen region with a 115 km horizontal spatial resolution.

Finally, mean seasonal and annual temperature anomalies (departure from the average of the 1979–2001 period) were also calculated from the satellite data for the area of Greece and the NH using the same method as with the ground measurements. It should be mentioned that since satellite data are available from January 1979, it is not possible to calculate the mean winter value of 1979; hence the period under examination is limited to 1980–2001.

2.2 Pressure data

The pressure series used in this study to calculate circulation indices and evolution of pressure in surface and upper levels over the Mediterranean region are Trenberth's NH monthly sea-level pressure (SLP) gridded values from the National Center for Atmospheric Research (NCAR) and the National Climatic Data Center (NCDC) monthly station data set. Monthly SLP gridded values were calculated on a 5° (72×15) latitude $\times$ longitude grid, whereas the NCDC monthly station data set consists of 4700 station records. In addition, time-series of monthly mean gridded 500 hPa height data on a 5° latitude $\times$ longitude grid for the NH were used. This grid was computed by Data Support Section (DSS) of the University Center for Atmospheric Research (UCAR) from the daily grids of various operational models and meteorological projects. The advantage of the gridded values is that they are less sensitive to errors in single station records.

2.3 Statistical tests for trend analysis

In order to examine any possible trend in the time series, the following three tests were applied:

i. *The first test* is the basic linear regression-based model in which time t (in years) is taken as the independent variable and temperature Y_t, is taken as the dependent variable. Under the usual regression assumptions, that is, when the residuals are independent and normally distributed with mean zero and variance σ^2, the estimated standard error of slope $\hat{b}$ of the regression line is given by

$$\hat{s}_1(\hat{b}) = \left[\frac{\sum_{t=1}^{n}(Y_t - \hat{a} - \hat{b}t)^2}{(n-2)\sum_{t=1}^{n}(t-\bar{t})^2}\right]^{1/2} \quad (1)$$

where $\hat{a} = \overline{Y} - \hat{b}\bar{t}$. The test of the null hypothesis H_o: $b = 0$ is based on the fact that $\hat{b}/\hat{s}_1(\hat{b})$ is distributed as Student's t with $n-2$ degrees of freedom when the null hypothesis is true. In fact, the hypothesis H_o: $b = 0$ is rejected when the ratio $t_1 = \hat{b}/\hat{s}_1(\hat{b})$ is greater than the critical value $t_{n-2;a/2}$ for a two-tailed t-test, where a is the level of significance (95% or 99%).

ii. *The second test* constitutes a stricter criterion since it assumes that residuals are not normally distributed and there is autocorrelation among them that has to be taken into account in the regression analysis. In this case Grenander (1954), Gryer (1986) and Bloomfield and Nychka (1992) suggest a different method for estimating the standard error of $\hat{b}$ that is not based on the independent error assumptions of regression analysis. Specifically, it can be seen that the standard error of $\hat{b}$ is given by

$$\hat{s}_2(\hat{b}) = \left\{\frac{12}{n(n^2-1)}\left[\gamma_o + \frac{24}{n(n^2-1)} \sum_{s-2}^{n}\sum_{t-1}^{s-1}(t-\bar{t})(s-\bar{t})\gamma_{s-t}\right]\right\}^{1/2} \quad (2)$$

where γ_k denotes the k^{th} autocovariance of the residuals E_t given by

$$\gamma_k = \frac{1}{n}\sum_{t=1}^{n-k} E_{t+k}E_t \quad (3)$$

The disadvantage of the estimator in Eq. (2) is that the estimated autocovariances γ_k are quite biased for large k. The null hypothesis H_o: $b = 0$ is rejected when the ratio $t_2 = \hat{b}/\hat{s}_2(\hat{b})$ is greater than the critical value $t_{n-2;a/2}$ for a two-tailed t-test, where a is the level of significance (95% or 99%).

iii. *The third test* applied was the Mann-Kendall rank statistic test, as it is proposed by Sneyers (1990). In particular, the Mann-Kendall rank statistic calculates all $u(d_i)$, $1 \le i \le n$, through a formula similar to the one referred by Michell et al. (1966). Before applying the test, the number m_i of terms Y_j in the series preceding each term Y_i $(i > j)$, is calculated such that $Y_j < Y_i$. The statistical test d_i is then given by the sum of the i first terms:

$$d_i = \sum_i m_i \quad (4)$$

and its distribution function under the null hypothesis is asymptotically normal, with mean and variance:

$$E(d_i) = i(i-1)/4, \qquad \text{var}(d_i) = i(i-1)(2i+5)/72 \quad (5)$$

Finally, the test calculates all $u(d_i)$, $1 \le i \le n$, given by the equation:

$$u(d_i) = [d_i - E(d_i)]/\sqrt{\text{var}(d_i)} \quad (6)$$

The null hypothesis H_o: $b = 0$ is rejected when the final value $u(d_n)$ of the $u(d_i)$ statistics for $i = n$ is greater – in absolute value – than 1.96 for a two-tailed test at 95% level of significance and 2.58 for a two-tailed test at 99% level of significance, where n is the length of the time series. The graphical representation of all $u(d_i)$, $1 \le i \le n$, is denoted as C_1.

The Mann-Kendall rank statistic is considered the most appropriate (Goosens and Berger, 1986) for the analysis of trends in climatological time series or for the detection of a climatic discontinuity, which according to Michell et al. (1966), is "a climatic change that consists of a rather abrupt and permanent change during the period of record from one average value to another". In order to localize the beginning of the change, the same principle applied for the $u(d_i)$ statistic is adapted to the retrograde series. The graphical representation of the retrograde series $u'(d_i)$, is denoted as C_2. When the values of the $u(d_i)$ become significant (greater than 1.96 for a two-tailed test at 95% level of significance), an increasing or decreasing trend can be observed depending on whether $u(d_i)$ is increasing or decreasing. In the absence of any trend in the series, the curves C_1 and C_2 generally overlap several times. However, in the case of a significant trend, the intersection of these curves localizes the change and allows the identification of the year when the trend or change starts.

2.4 Pressure indices

We used some circulation indices with the aim of relating the variability of air temperature with air-pressure patterns over the Mediterranean. The air-pressure station series used to construct the indices were tested by means of the Alexandersson homogeneity test (Alexandersson, 1986). Three indices were used in this study, the NAOI, the MOI and the MCI. The NAOI and MCI were obtained on a monthly basis as differences between standardized SLP station anomalies whereas the MOI is defined as differences between standardized 500 hPa geopotential height station anomalies.

a. *NAOI.* The North Atlantic Oscillation (NAO) is one of the large-scale modes of climate variability in the NH. It defines a large-scale meridional oscillation of atmospheric mass between the center of subtropical high surface pressure located near the Azores and the subpolar low surface pressure near Iceland. Synchronous strengthening (positive NAO state) and weakening (negative NAO state) have been shown to result in distinct, dipole-like climate change patterns between western Greenland/Mediterranean and northern Europe/Scandinavia (Walker, 1924; Walker and Bliss, 1932; van Loon and Rogers, 1978; Rogers and van Loon, 1979). In particular, a positive (negative) NAO is the result of a strong (weak) meridional pressure gradient leading to a colder, dryer (warmer, wetter) Greenland/Mediterranean sector and a warmer, wetter (colder, dryer) northern Europe/Scandinavia sector. A positive NAO implies more meridional storm tracks while a negative NAO implies more zonal storm tracks, which ultimately penetrate into the Mediterranean Sea (Alpert et al., 1990). Accounting for greater than one-third of the total variance of the SLP field over the North Atlantic, the NAO is most pronounced during the winter months because of an increased sea–air temperature contrast (Barnston and Livezey, 1987).

Because the signature of the NAO is strongly regional, a simple NAO index was defined as the difference between the normalized mean winter SLP anomalies at locations representative of the relative strengths of the Azores High and the Icelandic Low. Hurrell (1995) investigated the relationship between variations in the NAOI and the decadal trends in NH temperature and precipitation, successfully demonstrating the existence of a climate dipole. Results of the study performed by Cullen and deMenocal (2000) provided evidence that the NAO is not limited to the classic dipole, but rather extends beyond the north Atlantic and into the Middle East. They found that composite temperature and precipitation anomaly indices for the period 1930–1995 are significantly correlated with the NAOI.

In this study, seasonal (DJF, MAM, JJA, SON) indices of the NAO were based on the difference of normalized SLP between Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland since 1865, provided by the National Center of Atmospheric Research (NCAR) and is an update of the time series published in Hurrell (1995). The SLP anomalies at each station were normalized by division of each seasonal mean pressure by the long-term mean (1865–1984) standard deviation. Normalization is used to avoid the series being dominated by the greater variability of the northern station.

b. *MOI.* Conte et al. (1989) first described the ‘Mediterranean Oscillation’ (MO) as a teleconnection pattern with opposite pressure and rainfall anomalies between the central-western and eastern Mediterranean area. This dipolar oscillation in pressure patterns was further observed by several other researchers (Colacino and Conte, 1993; Piervitali et al., 1999; Kutiel et al., 1996; Douguedroit, 1998; Maheras et al., 1999a; Maheras and Kutiel, 1999). They introduced the MOI to describe this oscillation. It explains annual precipitation variability in the Mediterranean basin better than the NAOI. It concerns the pattern of the 500 hPa surface height monitored by the soundings at stations in Algiers and Cairo, assumed as representative of the Western and Eastern basin, respectively. When the pressure increases in the Western basin it decreases in the Eastern one and vice versa. This seesaw characterizes the Mediterranean Oscillation (MO). However, only the connection between the MO and the rainfall series in the Central-Western Mediterranean has been investigated up to now. The index used by Conte et al. (1989) to define the MO was the difference of normalized geopotential height anomalies of the 500 hPa surface at Algiers and Cairo. In fact, in order to calculate the Mediterranean Oscillation Index (MOI), we used the gridded reanalysis data provided by the DSS of UCAR, since the available data for Cairo and Algiers were incomplete. Drawbacks of using these data are that they are available only for the last 50 years and they describe a bipolar pattern using only one station's series.

c. *MCI.* In order to obtain an index more suitable for the central Mediterranean, Brunetti et al. (2002) defined a new index, the Mediterranean Circulation Index (MCI), as the normalized sea level pressure difference between one station lying in the northwestern Mediterranean and another in the southeastern Mediterranean. According to the quality (homogeneity and length) of the series, they selected the stations of Marseille and Jerusalem. As with the MOI, the correlation of the MCI with air temperature series has not been yet examined. In this study, the MCI was calculated using the NCDC monthly station data set.

3. Results

3.1 Temperature trends in surface observations

The three statistical tests were applied to the mean annual and seasonal time series of all the 20 stations for the period 1955–2001. The slope of the regression line was estimated by the linear regression analysis of the first test. Table 2 provides the magnitude of the linear trends and the values of the statistics t_1, t_2 and $u(d_n)$ for the annual and seasonal means of winter and summer (i.e. the main seasons rather than the transitional ones). Trends are considered statistically significant at the 95% level of significance – presented in bold and underlined characters in the table – when identified as such by the regression-based model and by at least one of the other two tests. This is due to the fact that the regression model provides statistically significant results in every case in which two or three tests result in a statistically significant trend. There are only a few stations with all three tests resulting in a statistically significant trend. The strict second test returns results that are not statistically significant in six summer series in contrast to the results of the other two tests. The correlogram of these time series shows an autocorrelation of the residuals at lag 1 with the exception of two stations (Aghialos and Kozani) in which no significant autocorrelation was found. As a consequence, the statistical significance of the trend in the summer series of these four stations is questionable, according to the more statistically rigorous second test.

The winter, summer and annual temperature time series, along with the 5-year moving average and the linear trend line, were graphically represented for each station but only the plots for Mytilene are presented here (Fig. 2).

Figure 3 presents the spatial distribution of the slope b (in °C/year) of the regression analysis for the annual and seasonal means (i.e. the main seasons since the transitional ones possess no statistically significant trend). The light grey areas indicate a significance level greater than 95%. Analysis of the full range of time series plots as well as Table 2 and Fig. 3, shows the warming or cooling trend at each station. No overall trend pattern is evident in the annual time series for the period 1995–2001 since there are stations with either a warming or cooling trend that is not statistically significant. In the winter time series, the cooling trend dominates in the majority of the stations; however, only 7 stations out of the 20, distributed mainly in western Greece and the southern Aegean Sea (Crete), present significant trends. For the same period, summer time series exhibit an overall warming trend for all stations; however, only 8 stations, located mainly in the Aegean Sea and eastern Greece regions, present statistically significant trends. Note that, in general, stations exhibiting significant trends in summer and winter are distributed over different parts of Greece. This indicates that a significant trend in a summer series determines to a great extent the pattern of the trend in the respective winter series and vice versa. Finally, no distinct overall trend was found for the time series of the transient seasons (spring and autumn) in which no-one station showed a statistically significant trend (not shown).

Table 2. Values of the slope b (in °C/year) of the regression analysis and the values of the statistics t_1, t_2 of the first and second test and the final value $u(d_n)$ of the Mann-Kendall statistic for winter, summer and annual mean surface temperature (1955–2001) (Statistically significant cases at 95% level of significance, provided by at least two tests, are presented in bold characters)

Station	Winter				Summer				Annual			
	b	t_1	t_2	$u(d_n)$	b	t_1	t_2	$u(d_n)$	b	t_1	t_2	$u(d_n)$
Aghialos	0.010	0.95	1.35	0.75	**0.017**	**2.15**	1.33	**1.98**	0.010	1.71	1.14	1.13
Agrinio	**−0.022**	**−2.05**	**−2.49**	−1.51	−0.002	−0.23	−0.11	−0.38	−0.009	−1.69	−1.19	−2.08
Alexandroupoli	−0.014	−1.15	−1.56	−0.83	**0.019**	**2.32**	1.23	**2.03**	0.002	0.26	0.21	−0.23
Araxos	**−0.019**	**−2.19**	**−2.21**	−1.86	0.006	0.77	0.47	0.71	−0.006	−1.17	−0.71	−1.02
Florina	−0.023	−1.35	−1.45	−1.18	0.001	0.10	0.06	−0.08	−0.009	−1.19	−0.75	−1.77
Ierapetra	**−0.018**	**−2.16**	**−2.11**	**−2.09**	0.012	1.56	0.82	1.11	−0.005	−0.92	−0.58	−1.22
Ioannina	**−0.020**	**−2.01**	**−2.80**	−1.71	0.006	0.56	0.39	0.28	−0.009	−1.72	−1.28	−1.93
Iraklio	**−0.016**	**−2.10**	**−2.28**	−1.75	0.000	0.07	0.03	−0.16	−0.005	−1.01	−0.65	−1.60
Kerkyra	0.000	0.05	0.07	0.38	0.020	2.50	1.18	1.71	0.010	2.06	1.21	1.16
Kozani	−0.005	−0.42	−0.42	−0.39	**0.035**	**2.79**	1.45	**2.36**	0.012	1.70	1.02	1.11
Kythira	−0.016	−1.95	−1.56	−1.60	**0.019**	**2.59**	1.25	**2.05**	0.002	0.32	0.18	−0.01
Larisa	−0.014	−1.25	−1.47	−1.07	0.003	0.37	0.19	0.27	−0.001	−0.20	−0.12	−0.56
Methoni	**−0.020**	**−2.54**	**−2.99**	**−2.30**	0.003	0.52	0.31	0.38	−0.008	−1.82	−1.13	−1.95
Milos	−0.020	−2.27	−1.88	−1.86	0.011	1.45	0.65	1.09	−0.005	−0.80	−0.42	−0.85
Mytilene	−0.020	−1.77	−1.79	−1.16	**0.025**	**3.17**	1.72	**2.58**	0.004	0.65	0.48	−0.08
Nat. Obs. Athens	−0.008	−0.79	−0.95	−0.58	**0.030**	**3.15**	1.38	**2.19**	0.013	1.97	1.17	1.04
Naxos	−0.008	−0.98	−1.07	−0.45	**0.020**	**3.15**	**2.01**	**2.87**	0.010	1.89	1.35	1.40
Skyros	**−0.030**	**−3.18**	**−4.84**	**−2.71**	**0.019**	**3.86**	**3.39**	**3.27**	−0.004	−0.86	−0.92	−0.60
Thessaloniki	−0.006	−0.60	−0.77	−0.58	0.004	0.54	0.25	0.10	−0.005	−0.87	−0.57	−1.27
Tripoli	−0.012	−1.15	−1.64	−0.85	0.009	0.87	0.55	0.36	0.004	0.62	0.46	0.16

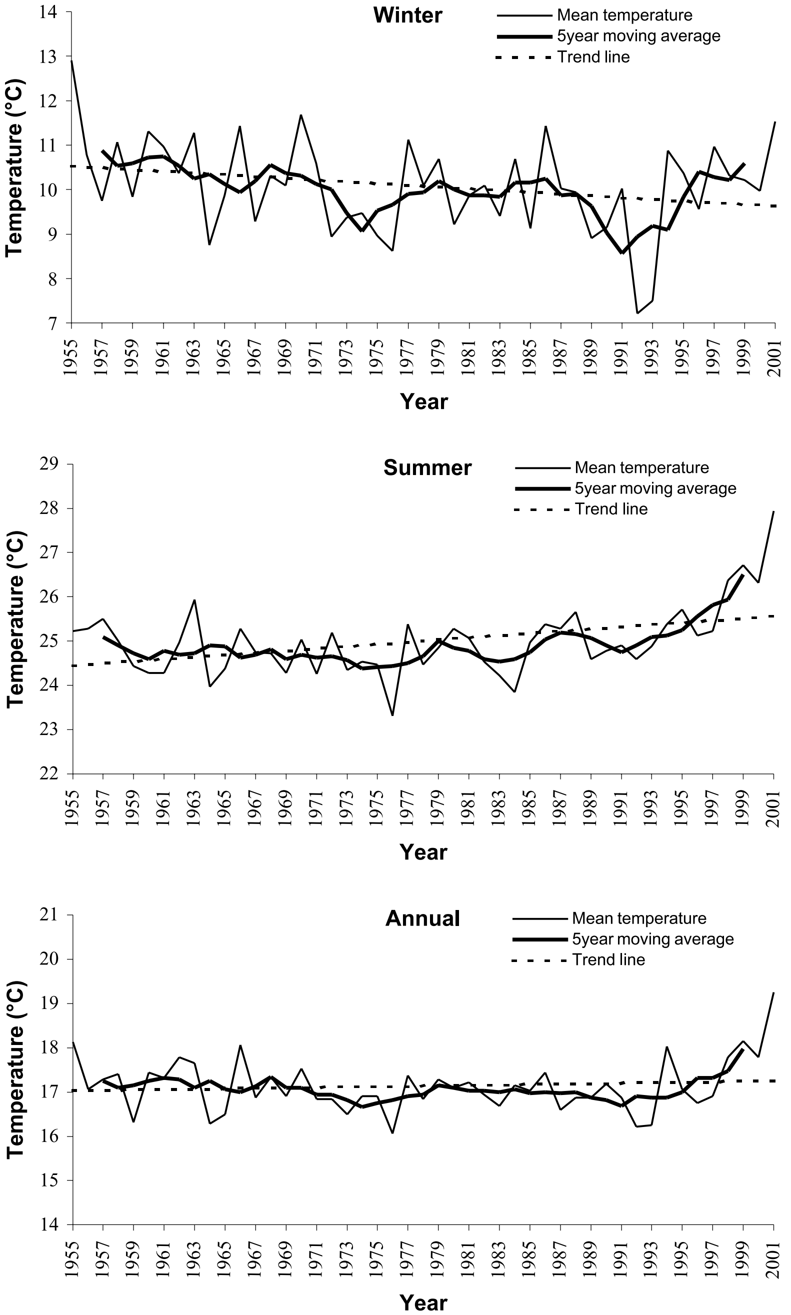

Fig. 2. Observed, 5-year moving average and trend line of winter, summer and annual mean air temperature at the station of Mytilene for the period 1955–2001

According to these results, it is clear that winter and summer exhibit a distinct overall trend in temperature time series. However, the temporal pattern and spatial distribution of the trend are different in each season. Winter shows an overall cooling trend whereas summer shows an opposite trend. The absence of a distinct overall trend in the annual values is due to the counterbalance of the two opposite trends.

The previous results cannot be thoroughly evaluated without a comparison with the corresponding trends in the NH in order to examine whether temperature trends in Greece match the overall warming trend detected at the hemispheric scale. The corresponding temperature time series for the NH are available as anomalies from the average of the 1961–1990 period, as this makes merging much easier. For comparison reasons, mean seasonal and annual temperature anomalies were also estimated for each of the 20 Greek stations and were averaged to derive the corresponding time series at the national scale. Presence of trend in each series was examined by applying the three statistical tests used in

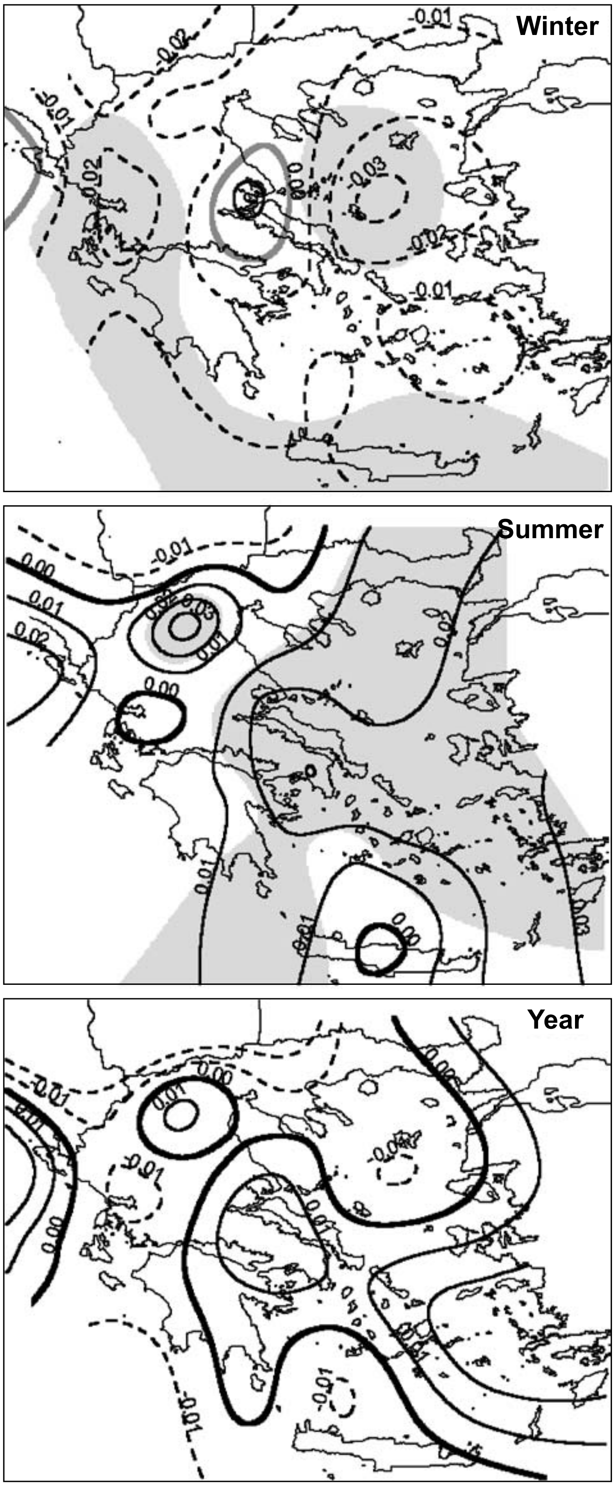

Fig. 3. Spatial distribution of the slope b (in °C/year) and significance levels (light grey levels indicate a significance level greater than 95%) of the regression analysis for the annual, winter and summer means (1955–2001)

the previous analysis and the results are presented in Table 3 for the mean annual, winter and summer series and plotted in Fig. 4. Table 3 indicates that temperature trends averaged over Greece do not match the statistically significant warming trends detected in annual and seasonal time series in the NH. In particular, winter series in Greece present a clear cooling trend, whereas, summer series exhibit an equivalent overall warming trend, but both seasonal trends are not statistically significant. As a result, the overall trend of the annual values is nearly zero. Finally, there is no distinct overall trend in the transient seasons (not shown).

Figure 4 shows a differentiation after the minimum in the annual values during the mid-1970s as the following warming trend was lower in Greece compared to the respective trend of the NH. This seems to be the result of the continuous cooling trend in the winter values in Greece during the entire period (1955–2001) in contrast to the winter temperature values for the NH, which began to increase after the mid-1970s (see Fig. 4). Summer series show a warming trend and a similar pattern for both areas, though this trend is not statistically significant for Greece. 1976 was the coldest year in both Greece and the NH for the period under examination. 2001 was the warmest year for Greece and 1998 for the NH. There is a rapid increase in temperature during the last four years of the period. The temporal behaviour of winter temperature anomalies in Greece is quite different to the corresponding patterns in the NH. The winter of 1992 was extremely cold and the winter of 1955 was extremely hot for Greece whereas the respective years for the NH were 1972 and 1998. On the contrary, extreme values for summer temperature anomalies are coincident for both areas. In particular, 1976 was the coldest and 1998 the warmest summer in both series. It is worth noticing again that the last four summers of the period 1955–2001 were the warmest during the whole period, contributing to a large extent to the respective high annual values.

It is not surprising that the temperature data over Greece do not match the overall hemispheric trend. It is well known that regional climate change is far from being homogeneous due to regional and large-scale atmospheric and oceanic transfer mechanisms. In addition, long-term linear trends may be superimposed by decadal – and shorter – scale variability, which also varies regionally.

Table 3. As Table 2 but for temperatures averaged over Greece and Northern Hemisphere. (Statistically significant cases at 95% level of significance, provided by at least two tests, are presented in bold and underlined characters)

	Winter				Summer				Annual			
	b	t_1	t_2	$u(d_n)$	b	t_1	t_2	$u(d_n)$	b	t_1	t_2	$u(d_n)$
Greece	−0.015	−1.76	−2.00	−1.42	0.013	2.12	1.08	1.60	0.000	−0.07	−0.05	−0.52
Northern Hemisphere	**0.013**	**4.66**	**2.77**	**3.93**	**0.010**	**5.58**	**2.63**	**3.69**	**0.011**	**6.41**	**3.22**	**4.69**

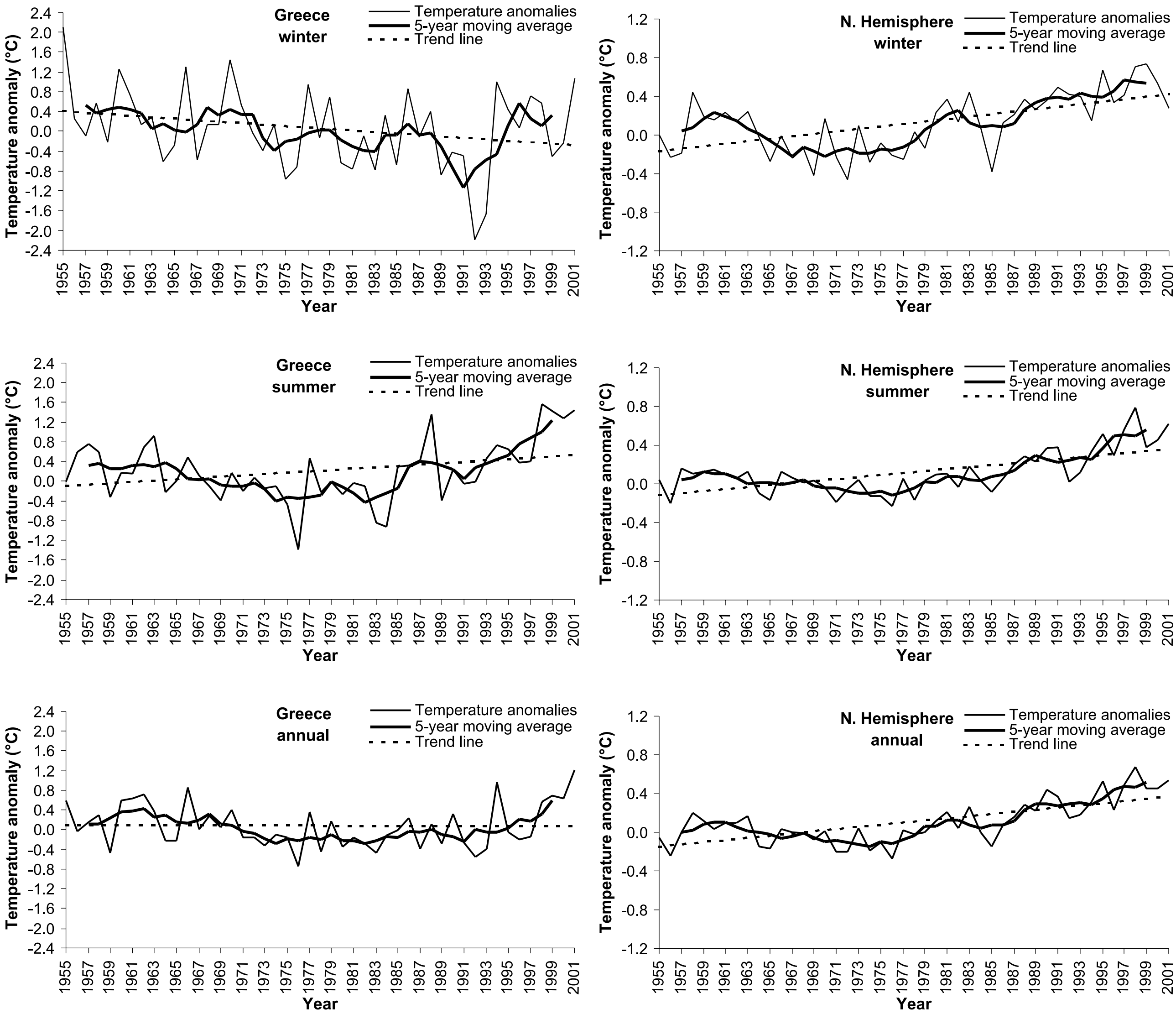

Fig. 4. Observed values, 5-year moving average and trend line of winter, summer and annual air temperature anomalies (departure from the average of the 1961–1990 period) in Greece and Northern Hemisphere for the period 1955–2001

A similar graphical analysis to that for the temperature series was applied to the $u(d_i)$ and $u'(d_i)$ statistics (curves C_1 and C_2 respectively) of each station, in order to identify the intersection of the curves and thus allow detection of the beginning of trend or change where present. Plots for Mytilene are given in Fig. 5. Analysis of the full range of figures shows the warming or cooling trend per station, as well as the approximate year when an abrupt temperature change

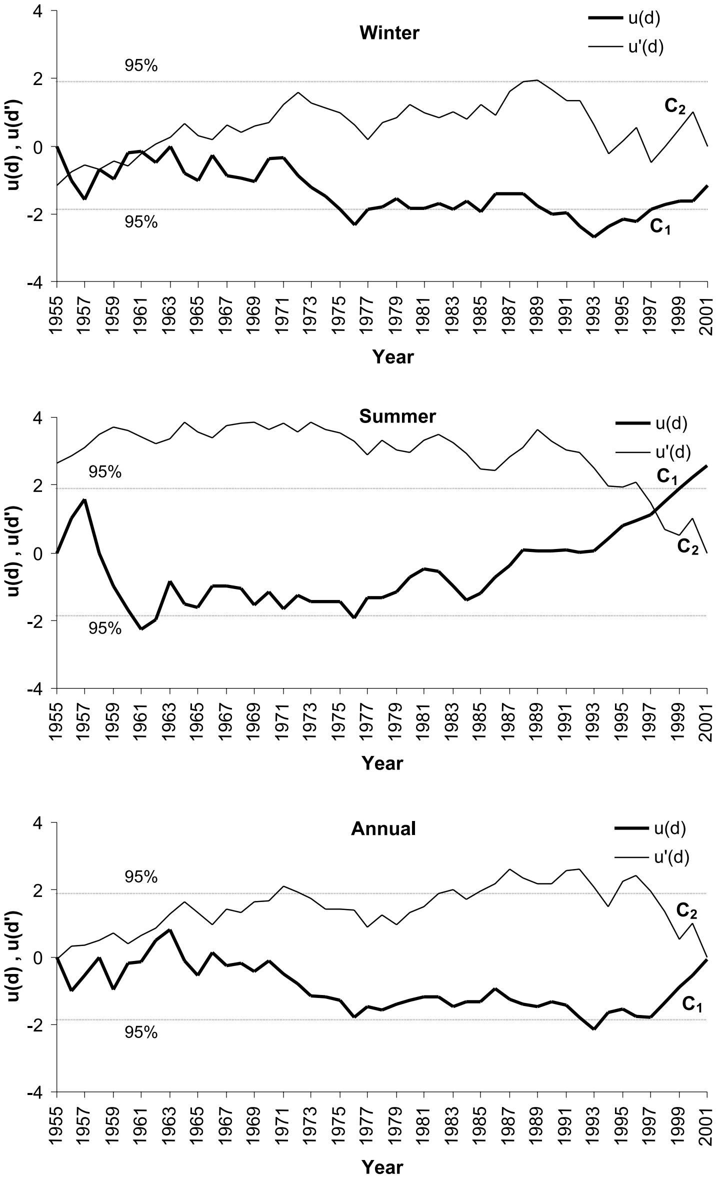

Fig. 5. Graphical representation of the series $u(d_i)$ and the retrograde series $u'(d_i)$ (denoted as C_1 and C_2) of the sequential version of Mann-Kendall, for winter, summer and annual mean air temperature at the station of Mytilene for the period 1955–2001

occurred. This information is summarized in Table 4 for the mean annual and seasonal series. Increasing and decreasing trends are represented by (+) and (−) respectively; each station is characterized by a year which reflects the initiation of a warming or a cooling trend. In some stations a second year is added, reflecting a year when a new change or trend was observed. Brackets in this year indicate that the change is not statistically significant at the 95% level. In addition, the asterisk in some stations denotes that there is no climatic change for the period.

Table 4 indicates that a cooling trend for annual values began in the early 1960s in half of the stations. A cooling trend for winter values began in the majority of the stations in the early 1960s whereas in some stations the trend began in the early 1970s. Summer time series may be divided into two categories. The stations in the first category present a cooling trend beginning around the late 1950s. Reversals in this cooling trend, though not statistically significant, are observed in the late 1990s. The second category comprises stations with a warming trend just in the last four years of the 1990s. It is worth noticing that these stations were found to exhibit a statistically significant warming trend for summer values over the entire period. As a consequence, this significant warming trend seems to be caused more by the very high temperatures in

Table 4. Approximate year of beginning of the warming or cooling according to the sequential version of Mann-Kendall rank statistic for mean annual and seasonal air temperature (1955–2001)

Station	Winter	Spring	Summer	Autumn	Annual
Aghialos	*	*	1997+	1965− (1999+)	*
Agrinio	1974−	*	1957− (2000+)	1967−	1958−
Alexandroupoli	1961−	*	1998+	*	*
Araxos	1963−	1958+ (1970−)	1963− (1998+)	1964−	1964−
Florina	1961−	*	1957− (2000+)	1967− (2000+)	1963−
Ierapetra	1971−	1964−	*	1961−	1964−
Ioannina	1963−	*	1958− (2000+)	1968−	1964−
Iraklio	1964−	*	*	*	1967−
Kerkyra	*	*	*	1963− (1998+)	*
Kozani	*	*	1997+	1968− (2000+)	*
Kythira	1961−	*	1996+	*	*
Larisa	1961−	*	1959+ (1998+)	1968−	1962−
Methoni	1971−	1956− (1971+)	1963− (1998+)	1964−	1967−
Milos	1963−	1970−	*	1962−	*
Mytilene	1961−	*	1998+	*	*
Nat. Obs. Athens	1956−	*	1998+	*	*
Naxos	*	*	1995+	*	*
Skyros	1972−	*	1994+	1968− (2000+)	*
Thessaloniki	1961−	*	1958− (2001+)	1969−	1963−
Tripoli	1961−	*	1956− (1998+)	1964− (1999+)	1962−

* No abrupt change at the 95% level of significance
+ Means a warming
− Means a cooling
( ) Approximate year of a new change in a trend which is not statistically significant

Table 5. As Table 4 but for temperatures averaged over Greece and Northern Hemisphere

	Winter	Spring	Summer	Autumn	Annual
Greece	1962−	1964−	1957− (1997+)	1964−	1964−
Northern Hemisphere	1989+	1988+	1994+	1990+	1990+

the last four years rather than by a regular positive trend. The majority of the stations do not present any abrupt climate changes in the spring series, whereas a cooling trend began in many stations in the mid-1960s in autumn and in some of them was reversed during the late 1990s.

These findings are also supported by the results of the sequential Mann-Kendall analysis when applied to the seasonal and annual temperature anomalies averaged over Greece (see Table 5 and Fig. 6). In particular, winter, spring, autumn and annual series exhibit a cooling trend, which began in the period 1962–64. The cooling trend in summer began in 1957 and started to be reversed after 1997. According to Fig. 6 and Table 5, the NH is mainly different to Greece due to the distinct warming trend in both seasonal and annual temperatures over the period 1955–2001 which seems to be caused mainly by the very high temperatures prevailing after 1988. Even though there is no overall warming trend at the national scale in Greece, it seems that after 1997 the country has entered period with a warm summer seasons that is in step with the abrupt climatic change observed in the NH since 1994 (see Table 5).

3.2 Temperature trends in satellite data series

The same analysis was applied to the satellite data in order to define any trend and years of a possible climatic discontinuity. Table 6a provides the magnitude of the linear trends for the annual and seasonal means for Greece and the NH, for 1980–2001. The annual, winter, and summer temperature series and the linear trend are shown in Fig. 7. The

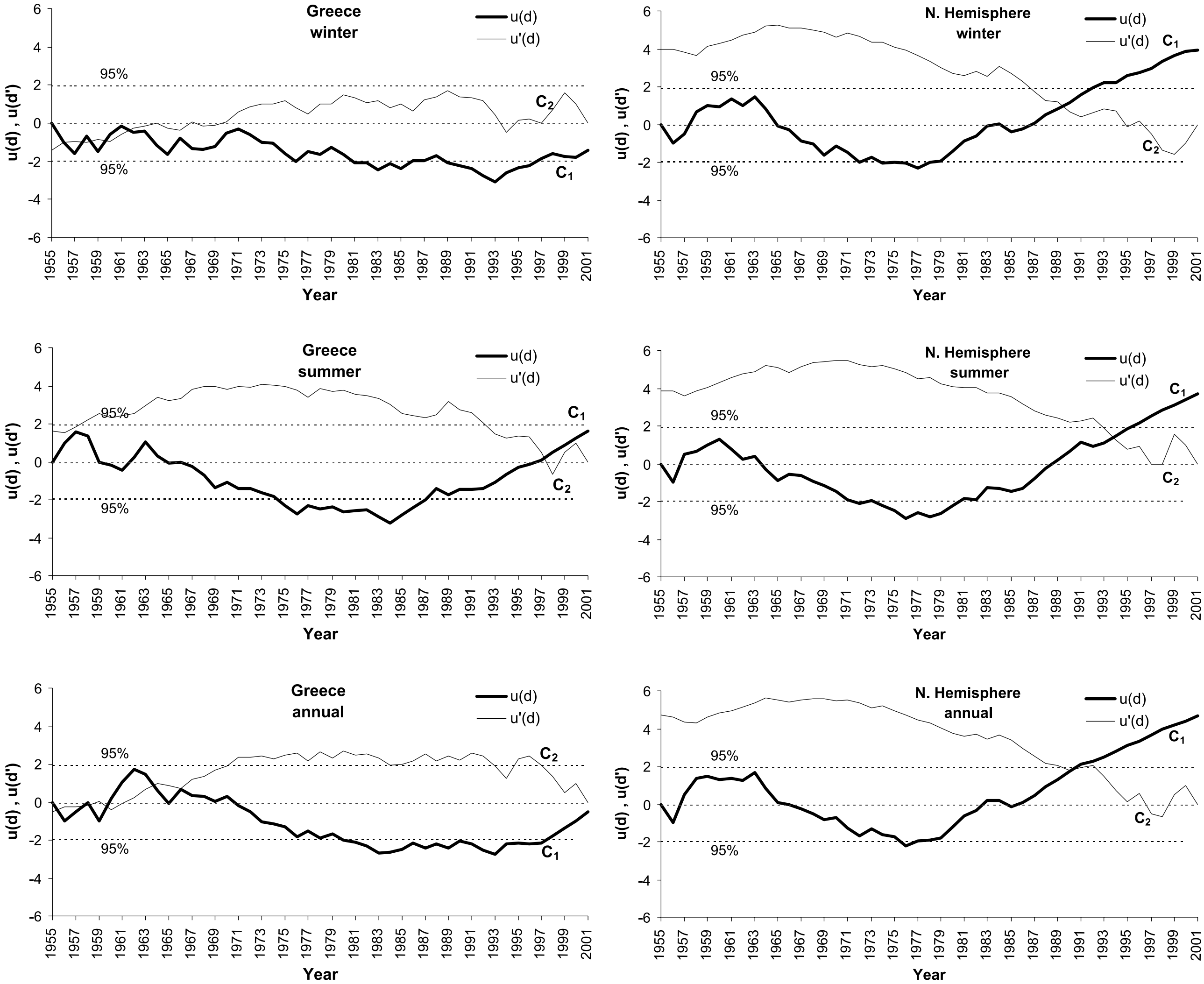

Fig. 6. Graphical representation of the series $u(d_i)$ and the retrograde series $u'(d_i)$ (denoted as C_1 and C_2) of the sequential version of Mann-Kendall, for winter, summer and annual mean air temperature anomalies (departure from the average of the 1961–1990 period) in Greece and Northern Hemisphere for the period 1955–2001

satellite time series for Greece shows a remarkable warming trend in the mean annual, winter and summer series. At the hemispheric scale, a warming trend is also discernible in the annual series, which is determined mainly by the respective increasing trend in the transitional seasons (spring and autumn). The magnitude of the warming trend found over Greece is, however, significantly larger than over the NH. According to the previous results, even though tropospheric temperatures are warming in both, Greece and the NH, the magnitude of the linear trends are significantly different. The results of the sequential Mann-Kendall analysis when applied to the seasonal and annual temperature anomalies from satellite over both areas, showed that the warming trend found in tropospheric temperatures for 1980–2001 started earlier in Greece (1988 for Greece and 1995 for the NH).

Comparison of the satellite and surface temperature series for the same period (1980–2001) (see Table 6b) match quite well for both, Greece and the NH, with only a difference in winter. The NH shows a warming trend in the annual temperatures from satellite for the lower troposphere which is slightly lower than for the surface records. This unexpectedly small difference (less than 0.08 °C per decade for annual values) between the satellite and surface based series is lower than the respective difference in the global temperatures (roughly 0.20 °C per decade). In contrast to the results for the NH, the satellite data for Greece show a warming trend

Table 6. Values of the slope b (in °C/year) of the regression analysis for seasonal and annual mean (**a**) satellite induced tropospheric temperature and (**b**) observed surface temperature for Greece and Northern Hemisphere for the period 1980–2001. (Statistically significant cases at 95% level of significance, provided by at least two tests, are presented in bold and underlined characters)

	Winter	Spring	Summer	Autumn	Annual
(a) Satellite induced					
Greece	**0.071**	0.044	**0.071**	0.028	**0.054**
Northern Hemisphere	0.009	**0.021**	0.019	**0.023**	**0.018**
(b) Surface observed					
Greece	0.035	**0.045**	**0.081**	0.026	**0.046**
Northern Hemisphere	**0.020**	**0.025**	**0.027**	**0.022**	**0.024**

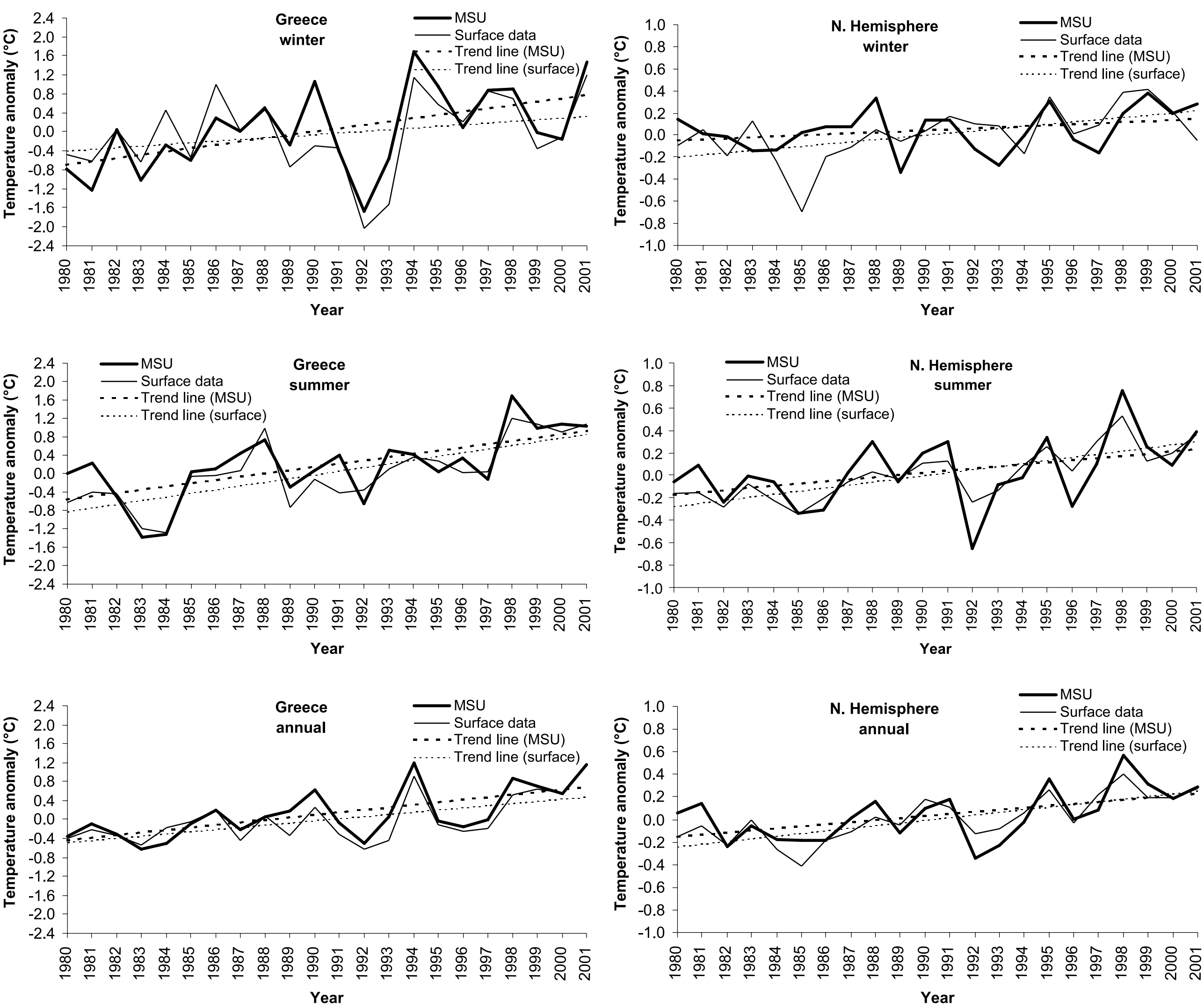

Fig. 7. Satellite induced tropospheric temperature anomalies, surface observed temperature anomalies and trend line of winter, summer and annual mean in Greece and North Hemisphere for the period 1980–2001

in tropospheric annual temperatures, which is slightly higher than in the surface temperature records. This difference is exclusively due to the respective large warming trend in winter temperatures over Greece, which is not present in the NH satellite data.

This differences between surface temperature measurements and satellite tropospheric temperatures have at least three possible interpretations (Santer et al., 2000). First, they may be an artifact, primarily related to residual data quality problems in either the surface or satellite data. Second, the difference may be real and due to the effects of natural internal variability and/or external forcing. Notice that satellite data reflect the average temperature of an atmospheric layer ranging from the surface up to 8 km in altitude whereas data from ground stations express the air temperature at 2 m above the surface. A third possibility is that some portion of the observed discrepancy is related to coverage differences between the satellite and surface temperature data. Several other reasons have been proposed by other researchers. The troposphere was found to show much larger variations to forcing from great volcanic eruptions, as El Chichón in 1982 and Mount Pinatubo in 1991, and carries the influence for a longer period (Christy and McNider, 1994; Jones, 1994b). In addition, the tropospheric temperature is highly influenced by the tropical region, while the surface record responds to the NH land distribution (Hurrel and Trenberth, 1998). Another possible reason is that the surface temperatures have warmed more than maximum temperatures, but the night-time inversions do not transmit this information to the troposphere (Hurrel et al., 2000). According to Trenberth et al. (1992), the land inversions de-couple the surface and the troposphere during the winter in the NH. All of these interpretations are not mutually exclusive.

3.3 Pressure evolution at the surface and upper levels in the Mediterranean Sea

The temperature trends identified over the Greek region can be related to the atmospheric circulation over the Mediterranean area by examining the evolution of sea-level pressure and the height of the 500 hPa surface. Figure 8 presents the sea-level pressure (SLP) trend slope over the Mediterranean Sea, for individual seasons for the period 1955–2001. Trend slopes were calculated by using Trenberth's NH monthly SLP gridded values from NCAR. The significance level was calculated using the linear regression-based model. The light grey areas indicate a significance level greater than 95%, and the dark grey areas indicate a significance level grater than 99%.

A positive annual trend (up to 0.04 hPa/year) with highly significant values over the entire Mediterranean basin is evident (Fig. 8a). The positive trend over the Mediterranean is mainly due to winter where the slope is up to 0.12 hPa/year (Fig. 8b), spring contributes less, with slopes up to 0.06 hPa/year (Fig. 8c). The positive pressure trend prevailing mainly over central-western parts of the Mediterranean agrees with the hypothesis (first proposed by Colacino and Conte, 1993) of an increase in the number and persistence of anticyclones in the region in recent decades, particularly during the winter.

In summer, the significant positive pressure trend is limited to the southeastern Mediterranean, the Middle East and Turkey (up to 0.04 hPa/year). During this season the local circulation of Etesean winds dominates over Greece as the thermal low of India extends over the southeastern Mediterranean, resulting in a north to northeasterly low-level airflow over Greece, which cools the area. The increasing trend in pressure indicates a less frequent expansion of the low over the southeastern Mediterranean and therefore a weakening of the Etesian winds and a subsequent increase in summer temperatures. This is in agreement with the decreasing frequency of the weather types which are responsible for the appearance of airflows bringing Etesean winds during the period 1958–1997, found by Maheras et al. (2000). The main increasing – though not strong – trend of the anticyclonic circulation types in summer over Greece (Maheras et al., 2000) supports this assumption and can be correlated with the general warming (but not statistically significant) trend found over Greece in this study.

Maps of the trend slope of the 500 hPa surface height over the Mediterranean Sea, for individual seasons, and for the period 1955–2001, are presented in Fig. 9. Trend slopes were calculated using the time-series of monthly mean gridded NH 500 hPa height data from UCAR. The results show a highly statistically significant increase of the annual 500 hPa surface height (up to 0.8 m/year) covering the Mediterranean basin (with the exception of its south-eastern part) reaching the highest value over the central-

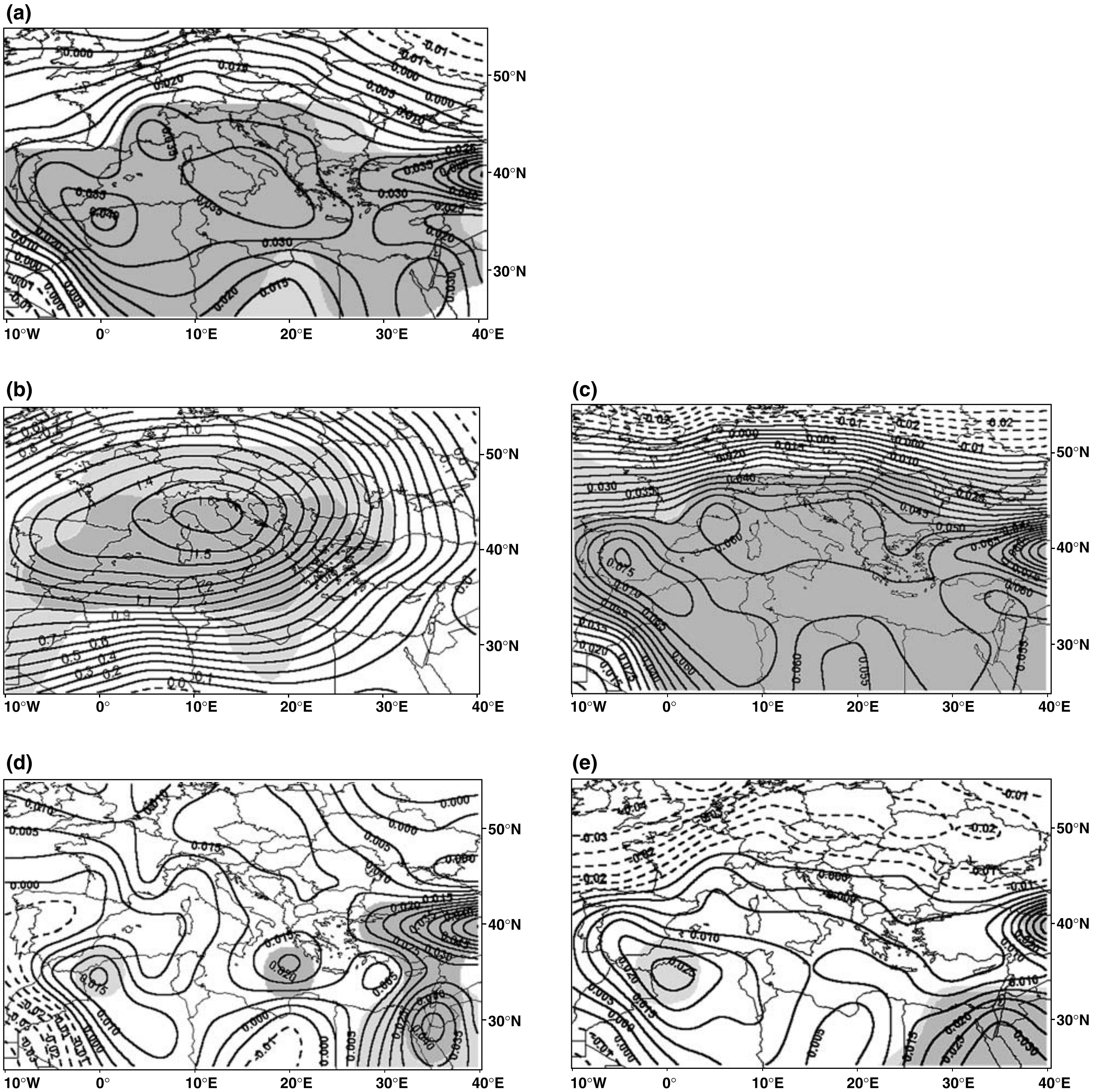

Fig. 8. Maps of sea-level pressure trends (hPa/year) and significance levels (light grey levels indicate a significance level greater than 95%, and the dark grey areas a significance level greater than 99%) over the Mediterranean in the period 1955–2001: (**a**) year, (**b**) winter, (**c**) spring, (**d**) summer and (**e**) autumn

western Mediterranean (Fig. 9a). This positive trend over the central-western Mediterranean is mainly due to the winter season where the slope is up to 1.6 m/year (Fig. 9b), whereas the summer and autumn season contributes to a lower extent, with slopes up to 0.6 m/year (Fig. 9d, e).

The positive trends are consistent with the respective increase in sea-level pressure for winter season and the year (Fig. 8). This is due to the strengthening of the southwesterly jet over the North Atlantic area; the western-central Mediterranean lies to the southeast in the right exit zone of this jet. This leads to an ageostrophic cross-isobar, northwest–southeast mass transport and therefore a rise in pressure in the lower troposphere, due to imbalance of the flow in the northeastern diffluent zone of this jet (Ryd-Scherhag divergence theory; Scherhag, 1948, 1952; Wanner et al., 1997). The observed rise of pressure, both at surface and upper levels, is likely to

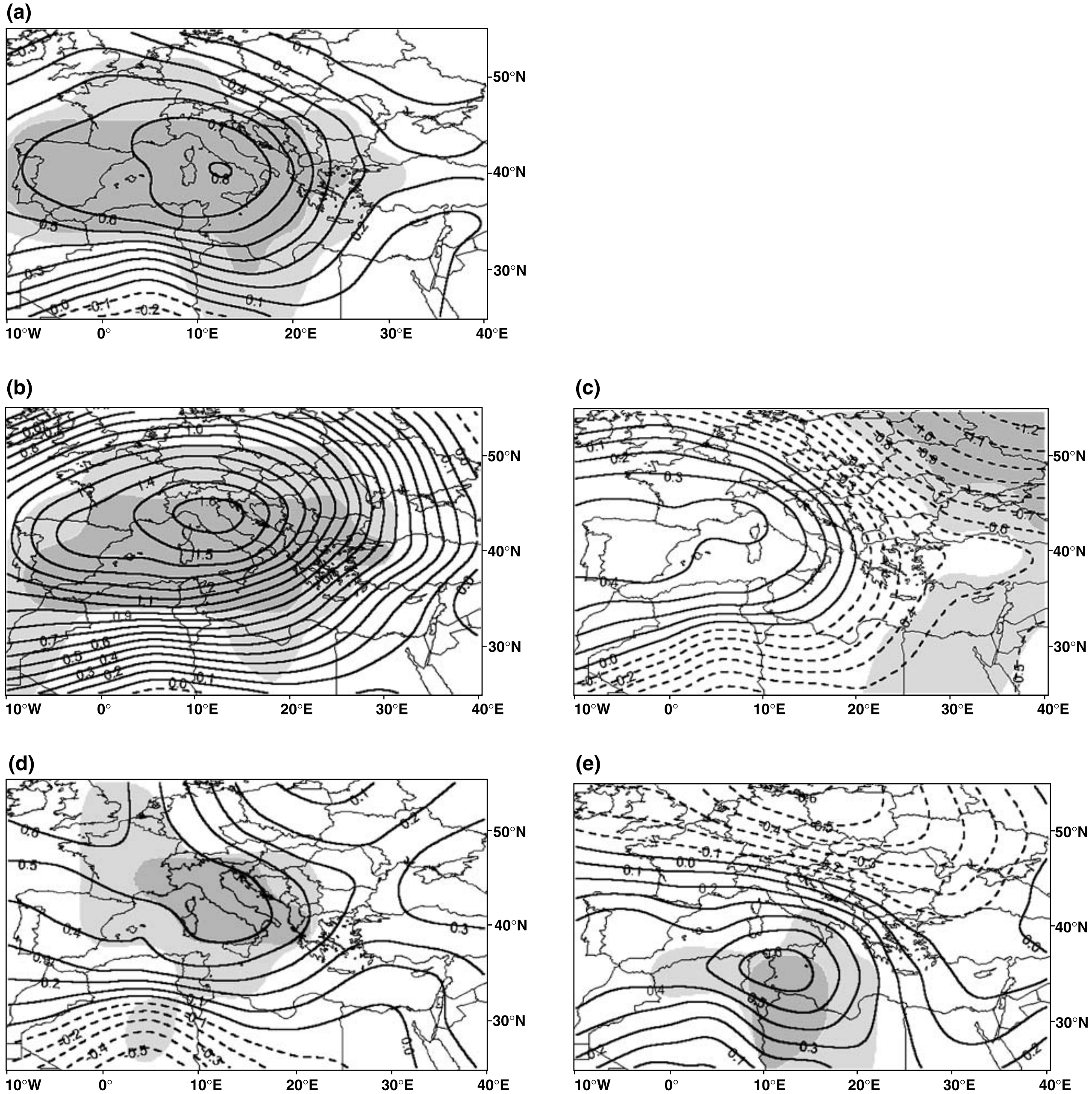

Fig. 9. Maps of the 500 hPa geopotential trends over the Mediterranean (m/year) and significance levels (light grey levels indicate a significance level greater than 95%, and the dark grey areas a significance level greater than 99%) over the Mediterranean in the period 1955–2001: (**a**) year, (**b**) winter, (**c**) spring, (**d**) summer and (**e**) autumn

be related to an increase of the frequency and persistence of anticyclones, particularly during the winter, that could be attributed to the Azores anticyclone (Colacino and Conte, 1993; Piervitali et al., 1997). The reduced thermal gradient between equatorial and polar latitudes, correlated with the enhancement of the greenhouse effect, could create an expansion of the subtropical anticyclonic belt (Webster, 1991). This process could also involve the Azores anticyclone, which should be more frequently observed in the Mediterranean region. As a result, a number of depressions that used to move along the meridional axis of the Mediterranean in winter, now move to the north.

The general cooling trend, although not significant, that occurs in winter over Greece is in accordance with the increasing trend of SLP over the area, a fact that is linked to an overall winter cooling in the Balkans (Leroux, 1993). For the eastern Mediterranean in particular, a decrease in cyclonic circulation is observed since 1960 for winter which can be connected to a change in the zonal circulation index for the North Atlantic and Europe (Sahsamanoglou and Makrogiannis, 1992). In particular, the winter cooling over Greece area can be attributed to the enhanced frequency of northwest or northeast continental, dry and cold airflows over Greece from northern Europe and western Russia. These flows are connected with the increase of the frequency and persistence of anticyclones over the central Mediterranean and Balkans (Maheras et al., 1999b). The winter geopontential height field in Fig. 9b supports these results.

3.4 Circulation indices and air temperature in Greece

Table 7 shows the correlation coefficients between annual and seasonal temperature, spatially averaged over Greece and the three circulation indices, NAOI, MOI and MCI. The correlation coefficients for all three indices are significant only in winter, due to the more coherent large-scale circulation typical for this season, and reveal a negative correlation with air temperature in Greece. The MCI and MOI explain more temperature variance in winter than the NAOI. In particular, a high significant correlation is evident for winter, with the proportion of explained variance being up to 37% for MCI and 31% for MOI. The previous results indicate that the Mediterranean oscillation in pressure patterns, either at the surface or at upper levels, is more representative of air temperature variability in Greece than the NAO and can be considered as a climatic forcing factor.

The link between temperature variability over Greece with regional (MCI and MOI) and large-scale (NAOI) oscillation modes is very reasonable from a physical point of view. A positive (negative) MCI in winter is the result of strong positive SLP anomalies prevailing over the western-central Mediterranean which induce a strong (weak) zonal pressure gradient leading to an enhanced (decreased) frequency of dry and cold airflow over Greece. As a result, during positive (negative) MCI values, winter in Greece becomes significantly cooler (warmer). In winters with positive MOI values, strong positive geopotential height anomalies prevail over the western-central Mediterranean, whereas negative anomalies are dominant over the eastern Mediterranean, extending northward to Russia. Anomalous mid-tropospheric northerly to northeasterly air currents from northern Europe and western Russia, driven by the high, are connected with the cooler air temperature over Greece (see also Fig. 9b). Analogously, opposite synoptic processes, with reverse climate behaviour, occur with negative MOI values as hot and dry air masses enter the eastern part of the Mediterranean (Kutiel and Paz, 1998; Krichak et al., 2000). Compared to the NAOI, the significantly higher correlation coefficient with the MCI implies that it is a better index for studying the relationship between winter temperature in Greece and pressure patterns. The Mediterranean oscillation patterns must not be seen as independent large-scale circulation modes, however, since they correlate significantly with the NH modes of the NAO (Dünkeloh and Jacobeit, 2003). On the other hand, they do not coincide with the NAO, but rather comprise those parts of the NAO linked with Mediterranean temperature variability. Both the MO, expressed as either MOI or MCI, and its connection with the NAO are best developed during winter and fade away towards summer and recover in autumn.

During positive values of the NAOI in winter, Greece becomes significantly cooler and drier as northerly airflow brings cold and dry continental

Table 7. Seasonal and yearly correlation of air temperature in Greece with circulation indices. Boldface and underlined values have a significant level of 95%

	Winter	Spring	Summer	Autumn	Year
NAOI	**<u>−0.373</u>**	−0.071	−0.092	0.133	−0.098
MOI	**<u>−0.553</u>**	0.063	0.101	−0.205	−0.119
MCI	**<u>−0.605</u>**	0.157	0.186	0.011	0.118

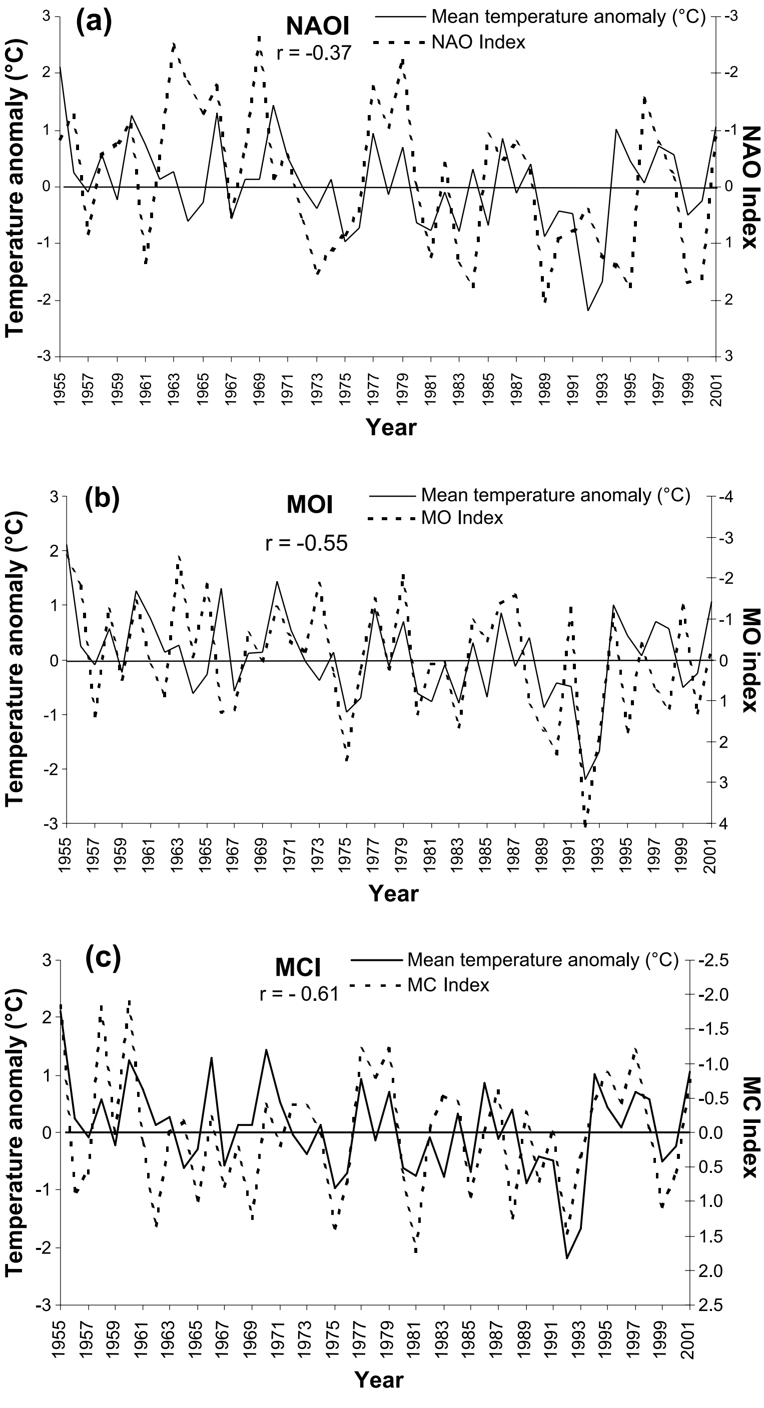

Fig. 10. Correlation between the winter temperature in Greece and circulation indices. (**a**) NAOI, (**b**) MOI and (**c**) MCI

air into the Mediterranean area. The more zonal trajectories of Atlantic heat and moisture during negative NAO phase winters bring anomalously warmer and wetter conditions to Greece. This connection between Greece and the North Atlantic sector is not the easternmost limit of the NAO influence on Mediterranean climate, since in the study of Cullen and deMenocal (2000) it was found that the NAO extends beyond the north Atlantic and into the Middle East and Turkey.

Figure10a shows that only major cold periods (1972–1976, 1980–1984, 1989–1993, 1999–2000) and major warm periods (1977–1979, 1986–1988, 2001) on decadal scales can be partially explained by the NAO. On the contrary, the MOI and MCI explain a high proportion of winter temperature variance as a result of the better significant correlation of winter temperature in Greece with the Mediterranean oscillation (Fig. 10b, c). Finally, the trend analysis only showed statistically significant rising trends for the MOI and the NAOI.

A major conclusion here relates to the link between the circulation indices and air temperature over Greece. Recent temperature trends may be explained by temporal changes in some coupled patterns of variability, principally concerning winter. Thus, the observed, but not significant, general cooling trend in Greece is linked to a rising trend in the Mediterranean circulation indices which is connected with the hemispheric circulation modes of NAO.

4. Conclusions

In this study, trends of annual and seasonal air temperatures, at the surface and lower troposphere, for the period 1955–2001, were investigated with the use of three statistical tests. The influence of regional and large-scale circulation on the air temperature in Greece was also examined.

Analysis of the annual and seasonal surface temperatures at national and individual station levels demonstrate the existence of marked variations and trends in Greece.

- For individual stations, Greece exhibits a distinct overall trend in winter and summer temperatures, statistically significant only at a small number of stations (7–8). However, the pattern and the spatial distribution of the trend are different by season. Winter shows a clear cooling trend whereas summer shows an overall warming trend. The significant summer warming trend seems to be mainly caused by very high temperatures in the last four years of the record than by a regular long term positive trend. The absence of a distinct overall trend in the annual values is the result of the counterbalance of the two opposite trends in summer and winter.
- Identification of start years of trend or changes in annual temperature series, on a station level, shows that a cooling trend began in the early 1960s in half of the stations. The winter cooling trend in the majority of the stations began in the early 1960s, whereas in some stations the trend began in the early 1970s. Summer series comprise stations with cooling trends beginning around the late 1950s and reversing in the late 1990s, and some others exhibiting a warm conditions just in the last four years of the 1990s.
- At the national scale, surface temperature trends in Greece do not match the statistically significant warming trends detected in annual and seasonal values in the NH. In particular, winter series in Greece present a clear cooling trend, whereas, summer series exhibit an equivalent overall warming trend, however, both trends are not statistically significant. As a result, the overall trend of the annual values is nearly zero. Moreover, differences exist in the time evolution of the annual values after a minimum in the mid-1970s. The following warming trend was reduced in Greece, compared to the respective trend for the NH. The rapid increase in summer temperatures during the last four years of the period 1955–2001 should be considered here.
- At the national level Greece exhibits cooling trends in winter, spring, autumn and annual series, which began in the period 1962–64. A cooling trend in summer began in 1957, and was reversed after 1997.

Comparison between Greece and the NH shows that Greece does not follow the marked positive trends observed in the NH. This is in agreement with many studies that have found a difference for Greece to the rest of Europe, in that surface air temperature in Greece shows a slight negative trend over the 20th century (IPCC, 1996; Mitchell and Hulme, 2000; Giles and Flocas, 1984; Retalis et al., 1998). Even though there is no overall warming trend at the national scale for Greece (1955–2001), it seems that after 1997 the country has entered a warm period in parallel to the abrupt climatic warming which occurred in the NH since 1994. It is not surprising that the temperatures in Greece do not closely match the overall NH trends. It is well known that regional climate change is far from homogeneous, due to regional and large-scale atmospheric and oceanic transfer mechanisms. In addition, long-term linear trends may be obscured decadal – and shorter – scale variability, which varies from region to region.

Analysis of satellite temperature data for the period 1980–2001 for Greece and the NH show:

- Greece showed a remarkable warming trend in mean annual, winter and summer series. At the NH scale a warming trend is also discernible in the annual series, which is determined mainly by the respective increasing trend in the transitional seasons, spring and autumn. The magnitude of the warming trend in Greece is significantly larger than in the NH.
- The trends in the satellite series with the respective trends in the surface air temperature for the same period (1980–2001) match quite well for both Greece and the NH, with differences only in winter. The NH shows a warming trend in the annual satellite series for the lower troposphere which is slightly lower than the surface based temperature trends. In contrast, the satellite series for Greece show a warming trend in tropospheric annual temperatures which is slightly higher than the surface temperature trends. This difference is due exclusively to a respective large warming trend in winter in Greece which is not present in NH satellite data.

Gridded pressure and mid-tropospheric geopotential height series for the Mediterranean provide evidence of a significant positive trend over the central-western part of the Mediterranean mainly due to increases in winter. A general cooling trend, though not significant, occurs in winter air surface temperatures over Greece which is in accordance with the increasing trend of pressure over the area, both at the surface and upper levels. In particular:

- The winter cooling over Greece can be attributed to an enhanced frequency of northwest or northeast continental, dry and cold airflows over Greece from northern Europe and western Russia. These are connected with the increase of the frequency and persistence of anticyclones over the central Mediterranean and Balkans (Maheras et al., 1999b).
- In summer, a significant positive pressure trend occurs in the eastern and southeastern parts of the Mediterranean, indicating a less frequent expansion of the low pressure that occurs over the area and therefore a weakening of the Etesian winds in Greece, and a subsequent increase of summer temperatures. This assumption is supported by a slight increasing trend of anticyclonic circulation types in summer over Greece, during 1958–1997 as found by Maheras et al. (2000).

Analysis of three circulation indices (NAOI, MCI and MOI) indicates that the behaviour of winter temperatures in Greece are due to changes in atmospheric circulation. Recent temperature trends may be explained by temporal changes in some coupled patterns of variability (the NAO and MO), principally in winter. In particular:

- The NAOI explains a small proportion of temperature variance in Greece only in winter. It is therefore not the most appropriate index for understanding temperature variability in Greece.
- The MOI, and especially the MCI, capture a greater proportion of the winter temperature variance in Greece. Thus, the observed, but not significant, general cooling trend in Greece is linked to a rising trend in the Mediterranean circulation indices, connected to the hemispheric circulation modes of the NAO.

The link between temperature variability in Greece and the Mediterranean pressure oscillation is very reasonable form a physical point of view. A positive (negative) Mediterranean oscillation in winter is the result of strong positive anomalies of SLP and mid-troposphere geopotential heights prevailing over the western-central Mediterranean which induce a strong (weak) zonal pressure gradient leading to an enhanced (decreased) frequency of dry and cold airflows over Greece from northern Europe and western Russia. As a result, during positive (negative) Mediterranean oscillation phases, winter in Greece becomes significantly cooler (warmer).

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References

Alexandersson H (1986) A homogeneity test applied to precipitation data. J Climatol 6: 661–675

Alpert P, Neeman B, Shay-ell Y (1990) Climatological analysis of Mediterranean cyclones using ECMWF data. Tellus 18: 65–67

Barnston A, Livezey R (1987) Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Mon Wea Rev 115: 1083–1126
Bloomfield P, Nychka DW (1992) Climate spectra and detecting climate change. Climate Change 21: 275–287
Brunetti M, Maugeri M, Nanni T (2002) Atmospheric circulation and precipitation in Italy for the last 50 years. Int J Climatol 22: 1455–1471
Christy JR, McNider NT (1994) Satellite greenhouse signal. Nature 367: 325
Christy JR, Spencer RW, Braswell WD (2000) MSU Tropospheric temperatures: Data set construction and radiosonde comparisons. J Atmos Oceanic Tech 17: 1153–1170
Colacino M, Conte M (1993) Greenhouse effect and pressure patterns in the Mediterranean basin. Il Nuovo Cimento C 16: 67–76
Conte M, Giuffrida S, Tedesco S (1989) The Mediterranean Oscillation: impact on precipitation and hydrology in Italy. Proc. Conference on Climate and Water, vol. 1, Academy of Finland 9: 121–137
CRU, Climate Research Unit (1997) Annual 1995. Climate Monitor. 24(5). Norwich: Climate Research Unit
Cullen HM, de Menocal PB (2000) North Atlantic influence on Tigris-Euphrates streamflow. Int J Climatol 20: 853–863
Douguedroit A (1998) Que peut-on dire d'une oscillation Méditerranéenne? In: Alcoforado MJ (ed) Climate and environmental change. Evora: 135–136
Dünkeloh A, Jacobeit J (2003) Circulation dynamics of Mediterranean precipitation variability. Int J Climatol 23: 1843–1866
Giles BD, Flocas AA (1984) Air temperature variations in Greece. Part 1. Persistence, trend, and fluctuations. Int J Climatol 4: 531–539
Goosens Ch, Berger A (1986) Annual and seasonal climatic variations over the Northern Hemisphere and Europe during the last century. Annales Geophysics B: 385–400
Grenander U (1954) On the estimation of regression coefficients in the case of autocorrelated disturbance. Ann Math Stat 29: 252–272
Gryer JD (1986) Time series analysis. Boston: Duxbury Press, 286 pp
Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science 269: 676–679
Hurrell JW, Van Loon H (1997) Decadal variations in climate associated with the North Atlantic Oscillation. Climatic Change 36(3–4): 301–326
Hurrell JW, Trenberth KE (1998) Difficulties in obtaining reliable temperature trends: Reconciling the surface and satellite microwave sounding unit records. J Climate 11: 945–967
Hurrell JW, Brown SJ, Trenberth KE, Christy JR (2000) Comparison of tropospheric temperatures from radiosondes and satellites: 1979–1998. Bull Amer Meteor Soc 81: 2165–2177
IPCC (1996) Climate Change 1995: The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press
IPCC (2001) Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press
Jones PD (1994a) Hemispheric surface air temperature variations: a reanalysis and an update to 1993. J Climate 7: 1794–1802
Jones PD (1994b) Recent warming in global temperature series. Geophys Res Lett 21(12): 1149–1152
Krichak SO, Tsidulko M, Alpert P (2000) Monthly synoptic patterns associated with wet/dry conditions in the eastern Mediterranean. Theor Appl Climatol 65: 215–229
Kutiel H, Maheras P, Guika S (1996) Circulation and extreme rainfall conditions in the eastern Mediterranean during the last century. Int J Climatol 16: 73–92
Kutiel H, Maheras P (1998) Variations in the temperature regimes across the Mediterranean during the last century and their relationship with circulation indices. Theor Appl Climatol 61: 39–53
Kutiel H, Paz S (1998) Sea level pressure departures in the Mediterranean and the relationship with monthly rainfall conditions in Israel. Theor Appl Climatol 60: 93–109
Leroux M (1993) Sécheresse et dynamique de la circulation dans l'Hemispher Nord. La secherence en Méditerranée et dans le pays environnants. Publications de l'Association Internationale de Climatologie 6: 69–83
Luterbacher J, Xoplaki E, Burgard R, Schmutz C (2000) Connection between the large scale lower atmospheric circulation and the winter temperature variability over Greece: 1957–1997. Proc. 5th Greek Scientific Conference in Meteorology-Climatology-Atmospheric Physics. Athens, 28–30 September 1998, 81–88 pp
Maheras P, Xoplaki E, Kutiel H (1999a) Wet and dry monthly anomalies across the Mediterranean basin and their relationship with circulation, 1860–1990. Theor Appl Climatol 64: 189–199
Maheras P, Xoplaki E, Davies TD, Martin-Vide J, Barriendos M, Alcoforado MJ (1999b) Warm and cold monthly anomalies across the Mediterranean basin and their relationship with circulation. Int J Climatol 19: 1697–1715
Maheras P, Kutiel H (1999) Spatial and temporal variations in the temperature regime in the Mediterranean and their relationship with circulation during the last century. Int J Climatol 19: 745–764
Maheras P, Patrikas I, Karakostas Th, Anagnostopoulou Ch (2000) Automatic classification of circulation types in Greece: methodology, description, frequency, variability and trend analysis. Theor Appl Climatol 67: 205–223
Makrogiannis T, Bora-Senta E, Philandros T (1998) Analysis of the air temperature time series in Thessaloniki, Application of the ARIMA(p,d,q) models. (in Greek) Proc. 4th Greek Scientific Conference in Meteorology-Climatology-Atmospheric Physics. Athens, 22–25 September 1998, 219–224 pp
Michell JM, et al (1966) Climatic change. WMO Tech. Note 79, WMO No. 195. TP-100. Geneva, 79 pp

Mitchell T, Hulme M (2000) A country-by-country analysis of past and future warming rates. Tyndall Centre Internal Report. No. 1. November, UEA, Norwich, UK. Cited in: http://www.tyndall.uea.ac.uk/main.htm

Nicholls N, Cruza GV, Jourel J, Karl TR, Ogallo LA, Parker DE (1996) Observed climate variability and change. In: Houghton JT, et al (eds) Climate Change 1995: The Science of Climate Change. Report of IPCC Working Group I, Cambridge: University Press, 137–192 pp

Parker DE, Jones PD, Folland CK, Bevan A (1994) Interdecadal changes of surface temperature since the late nineteenth century. J Geophys Res 99: 14373–14399

Parker DE, Folland CK, Jackson M (1995) Marine surface temperature observed variations and data requirements. Climatic Change 31: 559–600

Piervitali E, Colasino M, Conte M (1997) Signals of climatic change in the Central-Western Mediterranean basin. Theor Appl Climatol 58: 211–219

Piervitali E, Colasino M, Conte M (1999) Rainfall over the central-western Mediterranean basin in the period 1951–1995. Part II: precipitation scenarios. Il Nuovo Cimento C 22: 649–661

Proedrou M, Theoharatos G, Cartalis C (1997) Variations and trends in annual and seasonal air temperature in Greece determined from ground and satellite measurements. Theor Appl Climatol 57: 65–78

Retalis D, Hatzioannou L, Pasiardis S, Nikolakis D, Asimakopoulos DN, Lourantos N (1998) Study of the Temperature Time Series in SE Greece and Cyprus. (in Greek) Proc. 4th Greek Scientific Conference in Meteorology-Climatology-Atmospheric Physics. Athens, 22–25 September 1998, 271–278 pp

Rogers JC, van Loon H (1979) The seesaw in winter temperatures between Greenland and northern Europe. Part II: some oceanic and atmospheric effects in middle and high latitudes. Mon Wea Rev 107: 509–519

Sahsamanoglou HS, Makrogiannis TJ (1992) Temperature trends over the Mediterranean region, 1950–1988. Theor Appl Climatol 45: 183–192

Santer BD, Wigley TML, Gaffen DJ, Bengtsson L, Doutriaux C, Boyle JS, Esch M, Hnilo JJ, Jones PD, Meehl GA, Roeckner E, Taylor KE, Wehner MF (2000) Interpreting differential temperature trends at the surface and in the lower troposphere. Science 287: 1227–1232

Scherhag R (1948) Wetteranalyse und Wetterprognose. Heidelberg: Springer

Scherhag R (1952) Die explosionsartigen Stratosphärenerwärmungen des Spätwinters 1952. Der Dtsch Wetterd US-Zone 38: 51–63

Sneyers R (1990) On the statistical analysis of series of observations. Tech. Note 143, WMO No. 415, Geneva, 192 pp

Spencer R (2002) Globally-averaged atmospheric temperatures. Cited in: http://www.ghcc.msfc.nasa.gov/MSU/msusci.html

Trenberth KE, Christy JR, Hurrell JW (1992) Monitoring global monthly mean surface temperatures. J Climate 5: 1405–1423

Van Loon H, Rogers JC (1978) The seesaw in winter temperatures between Greenland and northern Europe. Part I: winter. Mon Wea Rev 104: 365–380

Walker GT (1924) Correlations in seasonal variations of weather. IX. Memoirs Indian Meteorology Department 24: 275–332

Walker GT, Bliss E (1932) World weather V. Memoirs of the Royal Meteorological Society 4: 53–84

Wanner H, Rickli R, Salvisberg E, Schuepp M (1997) Global climate change and variability and its influence on alpine climate-concepts and observations. Theor Appl Climatol 58: 221–243

Webster PJ (1991) Low frequency variability in the tropics and extratropics. ECMWF Seminar Proceedings on Tropical and Extra-Tropical interactions, Reading, U.K. 167–220

WMO (1997) WMO Statement on the Status of the Global Climate in 1996. WMO-No. 858. Geneva: World Meteorological Organisation

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